10 FINDINGS AND RECOMMENDATIONS

The options for sequestering carbon are diverse. Some are being implemented already, and others will require advances in scientific and engineering disciplines. Many options will require long lead times prior to implementation. In this chapter we identify issues central to the development of an R&D program that would enable us to make viable carbon sequestration options available for the 2025 to 2050 time frame.

The existing R&D program should be expanded soon. If carbon sequestration is to have a significant impact, it will necessarily involve changes of a large magnitude. Decisions made today about the energy infrastructure are likely to be with us for the greater part of a century. New information will help us develop an infrastructure with the flexibility to operate in tandem with carbon sequestration options. Therefore, research should anticipate substantially any necessary carbon reduction efforts.

For carbon capture and sequestration to become a viable large-scale option, it must be cost-competitive, safe, and acceptable. The R&D program should be oriented toward understanding more fully the fate of sequestered CO_2 and the impacts it will have on the environment and on human safety, and toward developing options to ensure a flexible response.

Given the federal government's role in supporting high-risk R&D in the long-term national interest, a carbon sequestration research and technology development program should be significantly expanded on the strength of the eventuality that such technology will be needed in the energy marketplace some time in the first quarter of the next century. This message is consistent with a recent report of the President's Council of Advisors on Science and Technology and other

Vision

"To protect the climate cost-effectively, technology breakthroughs, technology incentives, and the elimination of barriers for the deployment of existing technologies are needed. Broad-based cooperative programs to stimulate markets and develop and disseminate new and existing technology to industrialized and developing countries must be a high priority" (World Resources Institute, British Petroleum, General Motors, Monsanto 1998).

investigations. We should begin this R&D now, because the options available in 2025 and beyond will be determined by research being conducted today.

The first section of this chapter discusses overarching issues that became apparent during the development of this preliminary road map. They are key aspects of carbon sequestration that must be acknowledged and addressed in the planning and implementation of an expanded R&D program. The second section presents our recommendations resulting from an analysis of the focus areas discussed in the previous chapters and from discussions during the workshops.

The implementation of carbon capture and sequestration science and technology must be based on public acceptance. Outreach and educational activities to the public concerning climate change and sequestration are important. Even though some strategies seem inherently beneficial (e.g., planting more forests and protecting wetlands), it may be a challenge to gain public acceptance of some sequestration options because of their large scale, the fact that they are new and may be viewed as adding costs without adding value, and uncertainties about their environmental consequences. Although some current sequestration activities are presumably safe and benign, such as the Sleipner West Project in the North Sea, other options have largely unknown consequences.

Some sequestration options with potentially large environmental impacts may evoke strong concerns from the public. Whether a sequestration option is successful will depend not only on predicted consequences but also on public acceptance, based upon understanding of benefits and costs.

10.1 FINDINGS

- **Carbon sequestration is a broad topic with many internal linkages; combining processes often can provide ancillary benefits**

The ancillary benefits of many carbon sequestration options are appealing. Thus one of the ways to improve the prospects for carbon sequestration is to combine different processes and benefits so that the larger system is more attractive than individual parts. One example is the increased production of oil that would result from the use of CO_2 for enhanced oil recovery or the enhanced production of methane from injecting CO_2 into coal beds—sequestering CO_2 while extracting fossil resources. Another example discussed in Chap. 6 on advanced biological processes is the energyplex, referred to by DOE as the "Vision 21 Plant," which is a series of modular plants (an industrial ecosystem) that integrate the production of power, heat, chemicals, and fuels to maximize the use of available energy while capturing and sequestering carbon emissions. Another example of combining processes would be using captured carbon to make construction materials or soil enhancements that would otherwise be unavailable.

As Fig. 8.1 in Chap. 8 illustrates, carbon sequestration involves many technological paths and connections or feedbacks. The need to connect processes is evident. Costs and capacities of alternative sequestration options must be based upon consistent assumptions. For instance, the characteristics of a particular CO_2 stream—its location, temperature, pressure, concentration, or impurities—may make it more suitable for sequestration in one type of sink, such as a geological formation, than in another, such as an ocean.

The number of disciplines involved in carbon sequestration R&D is large. Much can be gained by coordinating research programs with related scientific and engineering activities; for example, scientists studying the oceanic carbon cycle and deep sea injection may need to collaborate with the offshore energy companies developing deep-sea technology.

We found that many research topics involve critical links in several of the focus areas. The development of monitoring systems is important across all the focus areas, and advanced biological and advanced chemical topics have potential impacts in several focus areas. In addition, for sequestration options that cannot rely on taking CO_2 directly from the atmosphere, efficient CO_2 capture, separation, and transportation methods are critical. If the cost of capture is very high or the delivery system cannot accommodate the large amount of carbon that must be sequestered, no degree of cost reduction or efficiency improvement for any sequestration option would be sufficient for it to compete with other carbon reduction efforts. The costs for linking capture and separation to disposal in geologic formations or in the oceans, including compression plants and gas pipelines, have not yet been properly addressed.

- **Many carbon sequestration options can work within the existing infrastructure; other scenarios would require a new distribution system**

A primary benefit of many sequestration options is that they use the existing infrastructure; indeed, sequestration may allow for continued use of fossil fuels and may be based upon current infrastructure. Sequestration also is consistent with the development of new advanced fossil-fuel-fired generation plants. Sequestration is likely to start with the easiest opportunities, which may require few infrastructure changes, such as the Sleipner West project in the North Sea or improved agricultural and forestry practices.

Other scenarios might require significant infrastructure changes. For instance, shifting to hydrogen-powered transportation to reduce carbon emissions would require a new hydrogen distribution system. The issues in developing a new distribution system, perhaps by making it cost-competitive before it reaches a critical size, are outside the purview of this report, but they are significant. In addition, deregulation could lead to a switch from central station power generation to distributed generating systems (e.g., microturbines) for which capture and separation technologies could be prohibitively expensive. Systems approaches should address the vast materials requirements for some proposed technological solutions. For example, formation of $MgCO_3$ compounds from CO_2 emissions could require mining operations of unrivaled magnitude for the ores needed.

- **Carbon sequestration is an appropriate topic for government-sponsored R&D, which will be critical to successful implementation**

The prior findings suggest carbon sequestration is not a trivial challenge. The integration required to obtain industrial participation, address environmental issues, and gain public acceptance suggests that an expanded government initiative is needed. In addition, unlike for clean energy and energy efficiency, no economic or regulatory incentives exist at this time for carbon sequestration, suggesting the need for more governmental than private responsibility for support of research and technology development programs. This conclusion was also reached by the DOE-sponsored Stakeholders' Workshop on Carbon Sequestration held in June 1998 (Herzog 1998), at which industry sent a strong message that "the research agenda for the moment must be led, and funded, by government."

Most possibilities for carbon sequestration involve immature technologies and ideas. The carbon sequestration options include topics that are inadequately investigated compared with many other energy research areas, making the opportunities for significant breakthroughs high. To be successful in the long term, government-sponsored R&D must result in significant advances that will change the rules of the game. Although little private-sector R&D is under way at this time, there is evidence (witness recent announcements by BP/Amoco and others) that the private sector will attempt to implement carbon mitigation approaches that are known to be technically and economically feasible. Domestic and international forest projects also are being conducted by the electric utility industry. These may offer unique opportunities for an R&D program to identify complementary links to industrial practices that could lead to early demonstration opportunities.

- **Some carbon sequestration options could be used as near-term measures until other carbon management technologies, including other carbon sequestration technologies, can be implemented**

There is much we cannot predict with confidence about the reaction of the natural system to increases in atmospheric CO_2 concentrations. There may be "nonlinear" responses derived from positive feedbacks. An altered climate could bring an increased release of greenhouse gases through, for instance, more rapid mineralization of soil organic material, altered ocean currents, or offgassing of CO_2 and/or methane from permafrost regions.

If scientists were to predict with some degree of reliability that there would be a nonlinear response in the near future, it might result in the need to emphasize development and implementation of near-term sequestration alternatives even though the lifetime of the sequestered carbon might be less permanent than is desirable. In this case, one sequestration option might target R&D to provide techniques and technologies to stall the nonlinear response until some other more permanent solution could be implemented.

10.2 RECOMMENDATIONS

10.2.1 Beginning the R&D Program

The following recommendations should apply to the carbon sequestration research program.

- **Ensure that the carbon sequestration research program develops technologies and practices that are cost-effective**

and benign. For carbon sequestration to be a viable option, it must compete favorably with other carbon management programs with respect to cost and effectiveness. Carbon sequestration should be safe, predictable, reliable, measurable, and verifiable. Research programs should lead to these ends. To be cost-effective, the research program will need to reduce costs associated with the current separation and sequestration technologies and processes and support the development of new, innovative technologies and processes.

- **Ensure that the research is integrated with other, related research programs.** The research program will be linked to related, ongoing research programs so as to leverage the efforts. For instance, results from biomass or carbon cycle research could help in developing the biological understanding needed for terrestrial sequestration.

  The research program should be conducted collaboratively among the offices in DOE and with other government agencies. Ties to other countries through research programs or through scientific bodies, such as IEA's Greenhouse Gas R&D Programme, should be made. The research program should also collaborate with the research and other activities undertaken by the private sector.

- **Ensure that the research program is flexible and targets a wide variety of approaches.** Carbon sequestration is an immature field, so multiple approaches and scales are warranted. There are many prospects for significant advances. An expanded R&D program should be broad-based, including both basic and applied, theoretical, laboratory, and field-based research, and all sources and sinks. A robust R&D program is needed that has the flexibility to evolve over time as new scientific advances are incorporated into the overall energy system. For example, deregulation of utility companies may lead to market penetration by highly distributed power systems whose individual emissions would be difficult to capture, aggregate, and sequester. Changes in the availability of oil and in the use of nuclear power because of geopolitical reasons could alter the energy mix and the accompanying CO_2 emissions. Future demand for materials made from CO_2, such as acetate or bioplastics, may increase dramatically. Changes in other related technologies, such as batteries and fuel cells, will influence the effectiveness of various technology pathways. Our understanding of the safety and potential environmental consequences of various sequestration options will evolve. An approach is needed that has a long-term goal but has the flexibility to respond to changes in public policy and energy systems, as well as to the successes and failures of its own research activities.

- **Initiate field-scale investigations to help guide other carbon sequestration research and increase understanding of processes at the field scale.** An important facet of any carbon sequestration R&D program will be to include some early field-scale investigations. Some sequestration options may be sufficiently ready for pilot- or field-scale research, such as sequestering CO_2 in soils and vegetation, geological formations, or in deep coal beds from which methane is extracted. Selection of these investigations should be based on existing information and the opportunities for early results that could provide rapid assessment and feedback to fundamental R&D needs. Large-scale long-term field studies should test research concepts and reduce economic, environmental, and operational uncertainties associated with the new technologies.

- **Ensure that the research program develops an integrated approach to setting R&D priorities and evaluating the probability of success for different sequestration options.** One potential research topic is the development of an integrated framework for carbon sequestration. A context for the overall research program would be useful because so many of the issues cross disciplines and related activities. The integrative modeling would include investigations into life-cycle analysis, risk, uncertainty, and, to the extent possible, economics. One goal would be to generate a clear model of the carbon flows, including the form that the carbon takes (gaseous, compressed liquid, elemental, carbonate, clathrate, etc.). A second goal would be to keep track of the upstream "costs" associated with the carbon in the form in which it is found. It is important to measure the energy penalties associated with providing carbon in a particular form at any particular place in the system. This research would precede actual economic analysis of many of the more complicated sequestration options.

  The integrated approach to research should incorporate two cross-cutting R&D areas: (1) Developing new monitoring and analysis technologies and procedures to evaluate the efficiency and longevity of our technolgies. (2) Developing and enhancing models and simulation systems for all CO_2 sequestion activities to aid in understanding potential benefits and risks associated with large-scale use of these technologies.

- **Ensure that the results of the R&D program are provided to policymakers to aid them in developing policy and selecting the most efficient and effective solutions to the issues of climate change.** This report is not intended to modify the policy process that determines what, if anything, should be done about climate change. But those policy processes should be informed about the availability, costs, and ancillary benefits of various sequestration options. Research and reporting on monitoring, verification, effectiveness, and environmental consequences of carbon sequestration technologies and practices are an essential element in an iterative process, the goal of which is to help policymakers design more efficient and effective solutions to carbon management.

- **Include the magnitude of the impact of the carbon sequestration option among the criteria for setting research priorities.** Further development and refinement of this road map could include setting priorities for the research. Many priorities and discussions of staging—that is, which research topics should be conducted first and which should come later—are included in the focus area chapters 2–7. Chapter 8 offers further general criteria that could be used in setting priorities. Although sequestration will likely be achieved through the use of a number of technologies, only those research topics should be targeted that have the potential for significantly reducing CO_2 emissions with acceptable environmental impacts and costs (in either real dollars or energy losses). Longer-term research should focus on the benefits of sequestration mechanisms that will be effective on scales from multiple decades to millennia. Those approaches with shorter sequestration time horizons will provide important relief in the short term, but they must be augmented with more substantial solutions in the longer term.

- **Further develop and refine this road map.** This report is only a first step and should be enhanced by engaging a broader community in discussions of the various sequestration pathways outlined in the roadmap. The understanding of carbon sequestration is still in its early stages, and R&D pathways are still being formulated. Technology pathways are outlined in this road map, but more explicit pathways can be generated for some of the focus areas. Some explicit recommendations are made in the focus area chapters, but phasing of potential R&D schedules has not been done. The next step should include more intense participation by stakeholders, such as the private sector and nongovernmental organizations.

10.3 PRINCIPAL FOCUS AREA RECOMMENDATIONS

10.3.1 Separation and Capture of CO_2

There are numerous options for the separation and capture of CO_2, and many of these are commercially available. However, none has been applied at the scale required as part of a CO_2 emissions mitigation strategy, nor has any method been demonstrated for all the anthropogenic sources considered in this R&D map. Many issues remain regarding the ability to separate and capture CO_2 from anthropogenic sources on the scale required, and to meet the cost, safety, and environmental requirements for separation and capture. In our assessment of the scientific and technological gaps between the requirements for CO_2 separation and capture and the capabilities to meet these requirements, many explicit and specific R&D needs were identified.

- Geologic or ocean storage sequestration options that use a concentrated source of CO_2 require low-cost carbon separation and capture techniques to be viable options. The scale of the industrial system required to process gigatonnes of carbon warrants investigation into new solvents, adsorbents, and membrane separation devices for either pre- or post-combustion separation.

- A science-based and applications-oriented R&D program is needed to establish the efficacy of current and novel CO_2 separation processes as important contributors to carbon emissions mitigation. The focus must be on specific areas where long-term R&D will result in orderof-magnitude changes in cost and energy penalty reductions. Important elements of such a program include the evaluation, improvement, and development of chemical and physical absorption solvents, chemical and physical adsorbents, membrane separation devices with selectivity and specificity for CO_2-containing streams, molecular and kinetic modeling of the materials and processes, and laboratory-scale testing of the selected processes.

- Field tests are needed of promising new CO_2 separation and capture options in small bypass streams at large point sources of CO_2, such as natural gas wells and hydrogen production plants.

- Transportation and compression plant costs should be considered as part of the capture and separation process.

10.3.2 Ocean Sequestration

- The ocean provides a large potential reservoir. Active experiments are already under way in iron fertilization and other tests of enhanced marine biological sequestration, as well as deep CO_2 injection. Improvements in understanding marine systems will be needed before implementation of major marine sequestration campaigns. The key concern to be addressed is improved understanding of potential environmental impacts associated with CO_2 sequestration in the deep ocean.

- Field experiments of CO_2 injection into the ocean are needed to study the physical/chemical behavior of the released CO_2 and its potential for ecological impact.

- Ocean general circulation models need to be improved and used to determine the best locations and depths for CO_2 injection and to determine the long-term fate of CO_2 injected into the ocean.

- The effect of fertilization of surface waters on the increase of carbon sequestered in the deep ocean needs to be determined, and the potential ecological consequences on the structure and function of marine ecosystems and on natural biogeochemical cycling in the ocean need to be monitored.

- New innovative concepts for sequestering CO_2 in the ocean need to be identified and developed that are cost- and energy-efficient and have minimal impact on the environment.

10.3.3 Carbon Sequestration in Terrestrial Ecosystems

- The terrestrial biosphere is a large and accessible reservoir for sequestering CO_2 that is already present in the atmosphere. Natural carbon fluxes are huge, so that even small forced changes resulting from R&D advances would be very significant. It will be important to address the consequences of altering the natural flux.

- The terrestrial ecosystem is a major biological scrubber for atmospheric CO_2 (present net carbon sequestration is ~2 GtC/year) that can be significantly increased by careful manipulation over the next 25 years to provide a critical “bridging technology” while other carbon management options are developed. An increase in carbon sequestration to perhaps as much as 5 to 10 GtC/year could be possible as a result of directed R&D. Ecosystem protection is also important and may reduce or prevent loss of carbon currently stored in the terrestrial biosphere.

- Research on four key interrelated R&D topics is needed to meet goals for carbon sequestration in terrestrial ecosystems:

  — Increase understanding of ecosystem structure and function directed toward carbon allocation and partitioning, nutrient cycling, plant and microbial biotechnology, molecular genetics, and functional genomics.

  — Improve measurement of gross carbon fluxes and dynamic carbon inventories through improvements to existing methods and through development of new instrumentation for in situ, nondestructive belowground observation and remote sensing for aboveground biomass measurement, verification, and monitoring of carbon stocks.

  — Implement scientific principles into tools such as irrigation methods, efficient nutrient delivery systems, increased energy efficiency in agriculture and forestry, and increased byproduct use.

  — Assess ecosystem behavior in response to carbon sequestration strategies in an environment of a changing climate using a suite of models (including life cycle analysis) to integrate across scales from physiological processes to regional ecosystem management practices.

- Field-scale experiments in large-scale ecosystems are necessary to understand both physiological and geochemical processes regulating carbon sequestration based upon integrative ecosystem models. Such carbon sequestration experiments are needed to provide proof-of-principle testing of new sequestration concepts and integration of sequestration science and engineering principles.

- A digital environmental atlas is needed of quality-assured, verifiable, and georeferenced carbon biogeochemistry on a worldwide basis that integrates terrestrial systems with ocean and geological systems.

10.3.4 Sequestration in Geological Formations

Although there is extensive industrial experience in geologic sequestration of CO_2, many important issues must be addressed to reduce costs, ensure safety, and gain public acceptance. Implementation of the recommendations outlined will provide the information and operational experience needed to address these issues.

- Limited geological sequestration is being practiced today, but it is not yet possible to predict with confidence storage volumes and integrity over long time periods.

Many important issues must be addressed to reduce costs, ensure safety, and gain public acceptance.

- Fundamental and applied research is needed to improve the ability to predict, optimize, and monitor the performance of sequestration in oil, gas, aqueous, and coal formations. Elements of such a program include multiphase flow in heterogeneous and deformable media; phase behavior; CO_2 dissolution and reaction kinetics, micromechanics and deformation modeling; coupled hydrologic-chemical-mechanical-thermal modeling; and high-resolution geophysical imaging. Advanced concepts should be included, such as enhancement of mineral trapping with catalysts or other chemical additives, sequestration in composite geologic formations, microbial conversion of CO_2 to methane, rejuvenation of depleted oil reservoirs, and CO_2-enhanced methane hydrate production.

- A nationwide assessment is needed to determine the location and capacity of the geologic formations available for sequestration of CO_2 from each of the major power-generating regions of the United States. Screening criteria for choosing suitable options and assessing capacity must be developed in partnership with industry, the scientific community, and public and regulatory oversight agencies.

- Pilot-scale field tests of CO_2 sequestration should be initiated to develop cost and performance data and to help prioritize future R&D needs. The tests must be designed and conducted with sufficient monitoring, modeling, and performance assessment to enable quantitative evaluation of the processes responsible for geologic sequestration. Pilot testing will lay the groundwork for collaboration with industrial partners on full-scale demonstration projects.

10.3.5 Advanced Biological Processes

The 21st Century has been referred to as the "Century for Biology." Indeed, many new molecular tools have been developed that will aid in new discoveries and assist in providing solutions to key problems facing humankind and the planet. The difference that advanced biological techniques can make will be evident when they are integrated with land, subsurface, and ocean management practices. The following recommendations will promote cost-effective and stable biological solutions to carbon sequestration.

- Advanced biological techniques may produce improvements too radical to predict. Biologic processes can yield sequestered carbon products at the least cost. New carbon sequestration options could become feasible and others could be improved using advanced biological techniques.

- Research should be initiated on the genetic and protein engineering of plants, animals, and microorganisms to address improved metabolic functions that can enhance, improve, or optimize carbon management via carbon capture technology, sequestration in reduced carbon compounds, use in alternative durable materials, and improved productivity.

- The objectives and goals of the advanced biological research should be linked to those specific problems and issues outlined for carbon sequestration in geological formations, oceans, and soils and vegetation so that an integrated research approach can elucidate carbon sequestration at the molecular, organism, and ecosystem levels.

- Short-, mid-, and long-term goals in advanced biological research should be insituted so that a mimetic yardstick can be employed to assess scale-up issues, genetic stability in natural settings, and efficacy in the field.

10.3.6 Advanced Chemical Approaches

- Most carbon sequestration options rely on chemical reactions to achieve benign, stable, and inert products. Studies to enhance the relevant chemistry almost certainly will reduce the costs or increase the effectiveness of these options. Results from R&D on advanced chemical topics also may make it possible to generate useful and marketable byproducts.

- The proper focus of R&D into advanced chemical sciences and technologies is on transforming gaseous CO_2 or its constituent carbon into materials that either are benign, inert, long-lived and contained in the earth or water of our planet, or have commercial value.

  — Benign by-products for sequestration should be developed. This avenue may offer the potential to sequester large (gigatonne) amounts of anthropogenic carbon.

  — Commercial products need to be developed. These could include aggregate for protecting land from ocean encroachment; fertilizer made from NH_3, water, and CO_2; and other products for which there may be large-scale uses. This topic probably represents a lesser potential (millions of tonnes) but may result in collateral benefits tied to pollution prevention.

- The chemical sciences can fill crucial gaps identified in the other focus areas. In particular, environmental chemistry is an essential link in determining the impact and consequences of these various approaches. Studies to address the specific gaps identified in Chap. 7 should be conducted to ensure that other focus areas meet their potential.

10.4 REFERENCES

Herzog, H. J., ed. 1998. *Proceedings of the Stakeholders' Workshop on Carbon Sequestration*, MIT EL 98-002, Massachusetts Institute of Technology Energy Laboratory, June.

WRI (World Resources Institute) British Petroleum, General Motors, and Monsanto 1998. *Climate Protection Initiative: Building A Safe Climate, Sound Business Future*, Washington, D.C.